

# Phenomenology of the $U(1)'$ -extended MSSM

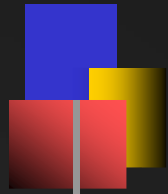
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- Madison**

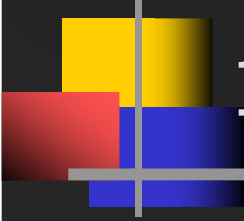
Seminar at KAIST (June 7, 2005)



# Outline

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1. MSSM and its limit
2.  $U(1)'$ -extended MSSM
3. TeV-scale  $U(1)'$  gauge boson
4. Implications of  $U(1)'$ -extended MSSM
5. Summary



# 1. MSSM and its limit

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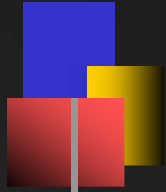
# Minimal Supersymmetric SM (MSSM)

- Minimal : Minimal extension of fields and symmetry
  - Minimal gauge group
    - : SM gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Minimal field contents
    - : (SM fields + **extra Higgs doublet**) & Superpartners
  - Soft breaking terms
    - : to break Supersymmetry
  - **R-parity**
    - : to avoid fast proton-decay

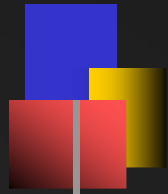


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- The only additions in the MSSM besides SUSY and its breaking terms



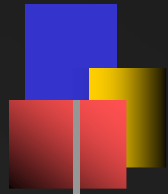
- Question :  
Assuming Supersymmetry at TeV-scale, would the MSSM be a Supersymmetric SM that can describe the TeV-scale physics adequately?



# $\mu$ -problem of the MSSM

- MSSM superpotential :

$$W_{\text{MSSM}} = \lambda_E L H_1 E^C + \lambda_D Q H_1 D^C + \lambda_U Q H_2 U^C + \mu \mathbf{H}_1 \mathbf{H}_2$$



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$[0] \qquad \qquad [0] \qquad \qquad [0] \qquad \qquad [1]$





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$\mu$  : the only dimensionful parameter (i.e., it has a scale) in SUSY-conserving sector of the MSSM

- 
- Quadratic scalar potential :


$$V_{(2)} = \mu^2 (|H_1^0|^2 + |H_2^0|^2) + (\text{EW/TeV-scale SUSY-breaking terms})$$

To have Higgs VEV of EW-scale,  $\mu$  should be also EW-scale to avoid fine-tuning.

- Why SUSY-conserving parameter ( $\mu$ ) scale  $\approx$  SUSY-breaking parameter (soft terms) scale?

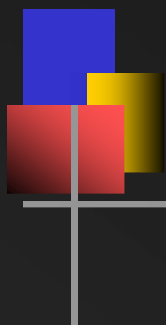
MSSM does not provide the answer. (the  $\mu$ -problem : fine-tuning problem of MSSM)

Kim, Nilles [PLB138 (1984) 150]

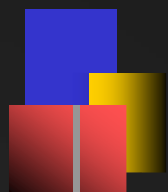


## Other issues in the MSSM (cosmology related)

- To have a sufficient first-order EW phase transition for the Electroweak Baryogenesis (EWBG),  $m_h$  should be only slightly above the LEP limit and  $m_{\text{stop}} < m_{\text{top}}$ . (fine-tuning in the parameter space of MSSM)
- In the minimal Supergravity model, the parameter space that can reproduce the acceptable CDM relic density is becoming increasingly narrow when combined with the LEP constraints (Higgs mass, chargino mass). (fine-tuning in the parameter space of CMSSM)



- The issues in the MSSM suggest :  
Even if nature holds Supersymmetry at TeV-scale, the MSSM may not fully describe the TeV-scale physics.



## What is next?

<b>Model</b>	SM	MSSM
<b>Fine-tuning problem</b>	gauge hierarchy problem	$\mu$ -problem
<b>Cure</b>	Supersymmetry	What (symmetry)?

- What (symmetry) would be cure of the fine-tuning in the MSSM?
- And what would be the naturally extended model of the MSSM that can suitably describe TeV-scale physics?



## 2. $U(1)'$ -extended MSSM

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- Consider a TeV-scale Abelian gauge symmetry,  $U(1)'$ , as a cure of the fine-tuning problem in the MSSM.



# U(1)'-extended MSSM

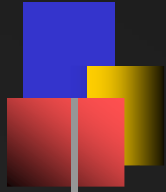
- Gauge group  
:  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$
- Field contents  
: (SM fields + extra Higgs doublet +  $Z'$  boson + Higgs singlet + Exotic fermions) & Superpartners
- Soft breaking terms  
: to break Supersymmetry
- R-parity  
: to avoid fast proton-decay






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- Introduction of the  $U(1)'$  symmetry requires extension in the field contents.
  - **$Z'$  boson** : gauge boson of  $U(1)'$
  - **Higgs singlet** : to break  $U(1)'$  symmetry spontaneously
  - **Exotic fermions** :  $U(1)'$  may need more fermions to cancel the anomaly

& Superpartners of the above fields

- 
- Specific  $U(1)'$  breaking scalar potential and exotic field contents are model-dependent. (We do not specify them here.)
  - Examples of the specific Supersymmetric  $U(1)'$  models :
    - Superstring-motivated model  
Cvetic, Demir, Espinosa, Everett, Langacker  
[PRD56 (1997) 2861]
    - $E_6$  GUT model  
Langacker, Wang [PRD58 (1998) 115010]
    - Multiple singlets model  
Erler, Langacker, Li [PRD66 (2002) 015002]


- 
- $U(1)'$ -extended MSSM superpotential :

$$W_{U(1)'\text{-MSSM}} = \lambda_E L H_2 E^C + \lambda_D Q H_2 D^C + \lambda_U Q H_1 U^C \\ + \mathbf{h_S S H_1 H_2}$$

- $\mu H_1 H_2$  is prohibited by the  $U(1)'$  charge assignment and  $\mu$ -term is replaced by the VEV of the Higgs singlet of TeV-scale.

$$\mu_{\text{eff}} = h_S \langle S \rangle \quad (\text{no } \mu\text{-problem})$$

(for example,  $Q'(H_1) = Q'(H_2) = -1$ ,  $Q'(S) = 2$ )

- 
- Instead of a discrete symmetry (of NMSSM), an Abelian gauge symmetry  $U(1)'$  is introduced.  $\rightarrow$  no domain wall
  - The Higgs singlet  $S$  [charged under only  $U(1)'$ ] is responsible to break the  $U(1)'$  spontaneously at the EW/TeV-scale and also plays the role of  $\mu_{\text{eff}}$ .
  - It naturally predicts a EW/TeV-scale  $Z'$  gauge boson :  

$$M_{Z'} = g_{Z'} [Q'(H_1)^2 v_1^2 + Q'(H_2)^2 v_2^2 + Q'(S)^2 s^2]^{1/2}$$

$$\sim g_{Z'} Q'(S) s \sim O(\text{EW/TeV})$$

(since  $\mu_{\text{eff}} = h_S \langle S \rangle \sim O(\text{EW})$ )      ( $\langle S \rangle \equiv s / 2^{1/2}$ )



## Sources of $U(1)'$

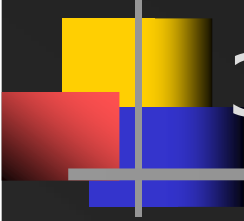
- $U(1)'$ -extended MSSM is a natural extension of the MSSM since, besides the bottom-up reasons ( $\mu$ -problem solution), many new physics models predict extra  $U(1)$  symmetries or Gauge bosons :
  - Grand Unified Theory
  - Extra dimension
  - Superstring
  - Dynamical EW symmetry breaking
  - Little Higgs



## Extended/Modified particle spectrum

- (1) Gauge boson sector ( $Z'$ )
- (2) Higgs sector (S)
- (3) Neutralino sector ( $Z'$ -ino, singlino)
- (4) Neutrino sector ( $U(1)'$  charged  $\nu_R$ )

We will discuss the phenomenology of these sectors with specific examples later.

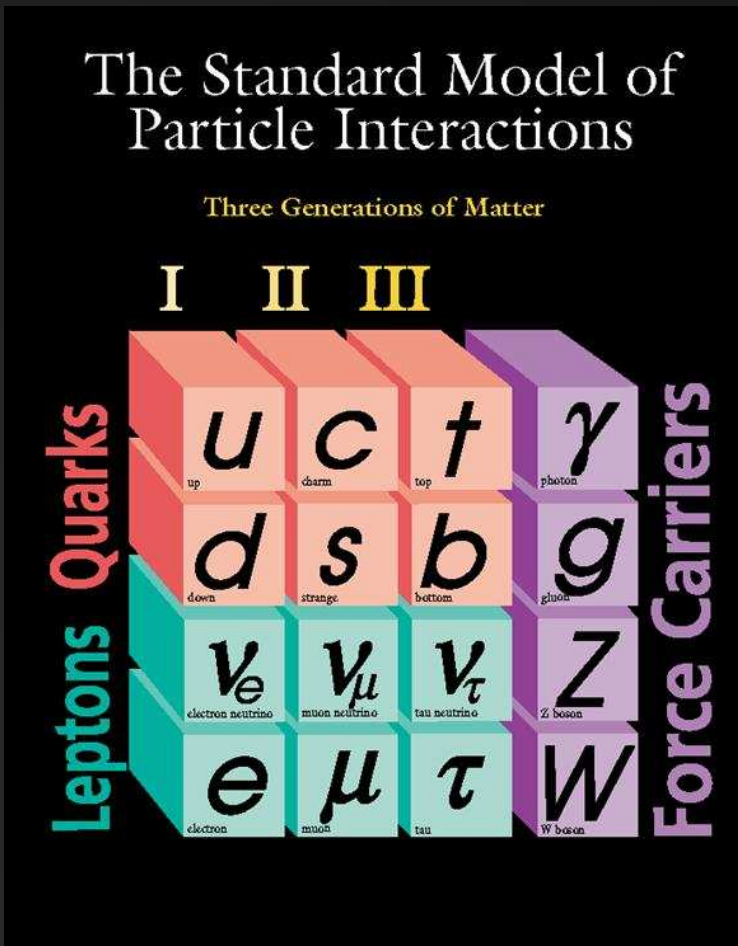


### 3. TeV-scale $U(1)'$ gauge boson

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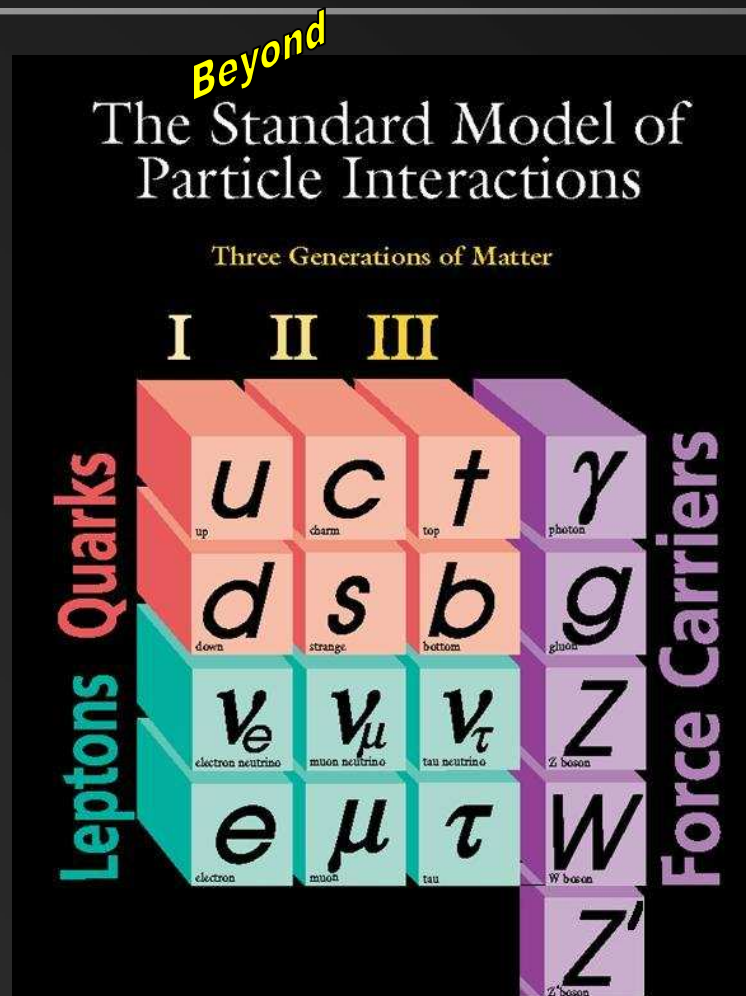


# New force carrier



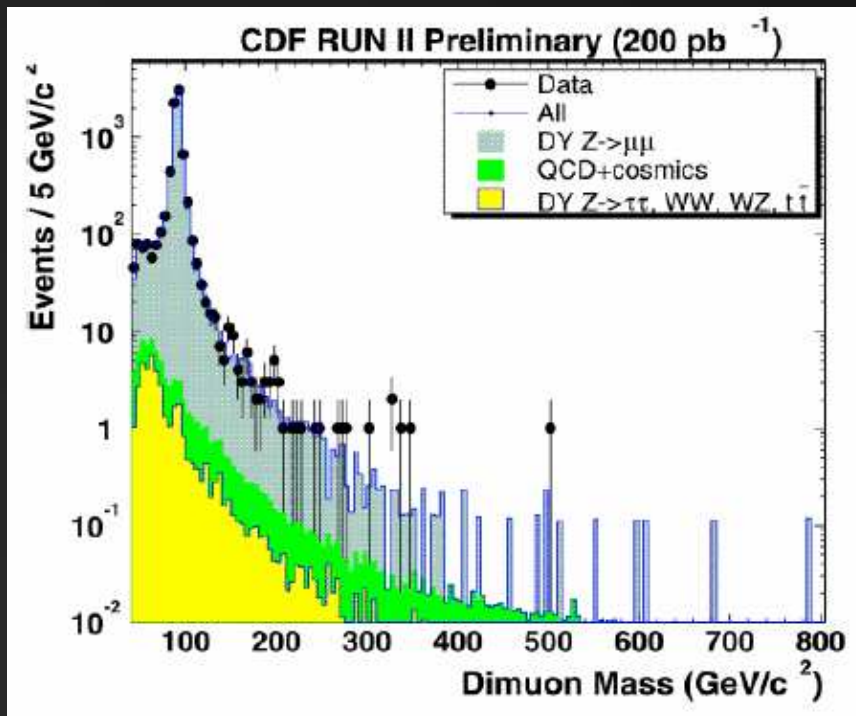
- $U(1)'$  is a new force and it needs a new force carrier ( $Z'$ ).
- The  $U(1)'$ -extended MSSM predicts the mass of  $Z'$  to be EW/TeV-scale.

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# Resonance by $Z'$



- The direct detection of  $Z'$  can be achieved by observation of the resonance (the most distinctive feature from the MSSM) in dilepton (dilepton or dijet) channels.

CDF Run2 Preliminary [Northwestern Workshop on  $Z$ 's (Nov '04)]

# CDF $Z'$ mass limits from dilepton search

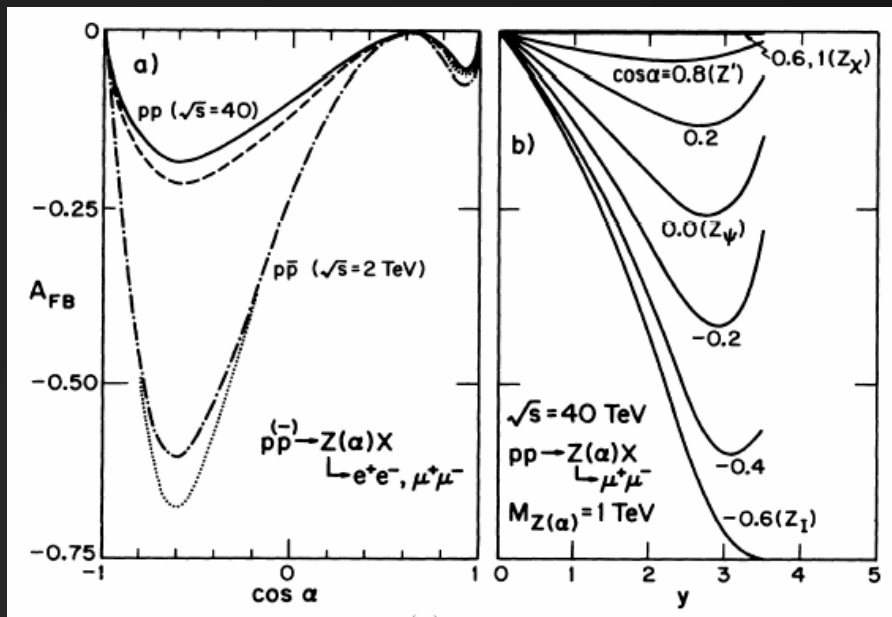
$E_6$  Mass Limit at 95% C.L. ( $\text{GeV}/c^2$ )

Model	$ee$	$\mu\mu$	$\ell^+\ell^-$
$Z'_{\text{SM}}$	750	735	815
$Z'_\psi$	635	600	690
$Z'_\chi$	620	585	670
$Z'_\eta$	655	640	715
$Z'_I$	575	540	610

CDF Run2 Preliminary  
[Northwestern Workshop  
on  $Z'$ 's (Nov '04)]

- The current limits of  $Z'$  mass are (600 ~ 800) GeV depending on models.
- Resonance is one of the cleanest signal.
- The LHC reach of  $Z'$  would be 2 TeV at day 1; it can search  $Z'$  up to 5 TeV.

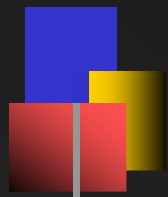
# Distinguishing models



- Forward-Backward asymmetry ( $A_{FB}$ ) contains information of the charge assignments.
- It is very useful in identifying gauge bosons (e.g., among  $E_6$  models).

Barger, Deshpande, Rosner, Whisnant [PRD35 (1987) 2893]

$A_{FB}$  in  $p$ - $p$  ( $p$ - $pbar$ )  $\rightarrow Z' \rightarrow l^+l^-$  versus  $E_6$  mixing angle and rapidity



## Other potential sources of resonance ( $Z'$ -like signals)

- Observing the resonance does not necessarily mean the existence of additional  $U(1)$  symmetry.
  - Part of non-Abelian gauge symmetry such as the 3<sup>rd</sup> component of  $SU(2)_R$
  - Kaluza-Klein excitations in extra dimension
  - String resonance
- Identifying the source of the resonance would be important.



## Z-Z' mixing

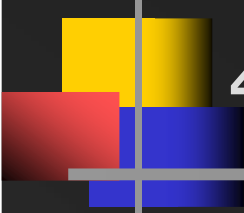
- $Z_1 = Z_{SM} \cos\delta + Z' \sin\delta$
- $Z_2 = -Z_{SM} \sin\delta + Z' \cos\delta$
- $\tan^2\delta = (M_{Z_{SM}}^2 - M_{Z_1}^2)/(M_{Z_2}^2 - M_{Z_{SM}}^2)$  : mix. angle of Z-Z'
- LEP result (precision measurement of coupling constants at the Z-pole) :  $|\delta| < (\text{a few}) \times 10^{-3}$



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- LEP result (precision measurement of coupling constants at the Z-pole) :  $|\delta| < (\text{a few}) \times 10^{-3}$
- Why so small mixing?
  - This is a natural value for sufficiently heavy  $Z'$  (about current experimental limit of  $600 \sim 800$  GeV or heavier)





## 4. Implications of $U(1)'$ -extended MSSM


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- (1) Higgs sector
- (2) Neutrino sector
- (3) Neutralino sector
- (4) Gauge boson sector [CP & FCNC]



## (1) Higgs sector

- Higgs singlet (S) is added to break  $U(1)'$  symmetry spontaneously.
- Higgs singlet does not interact with other MSSM particles except Higgs doublets ( $W = \dots + h_s S H_1 H_2$ ).
- The mixing of Higgs doublet and singlet under  $U(1)'$  symmetry modifies the masses and couplings of the physical states of Higgs.
  - (ex-i) Theoretical upper bound on the Higgs mass
  - (ex-ii) LEP2 lower bound on the Higgs mass

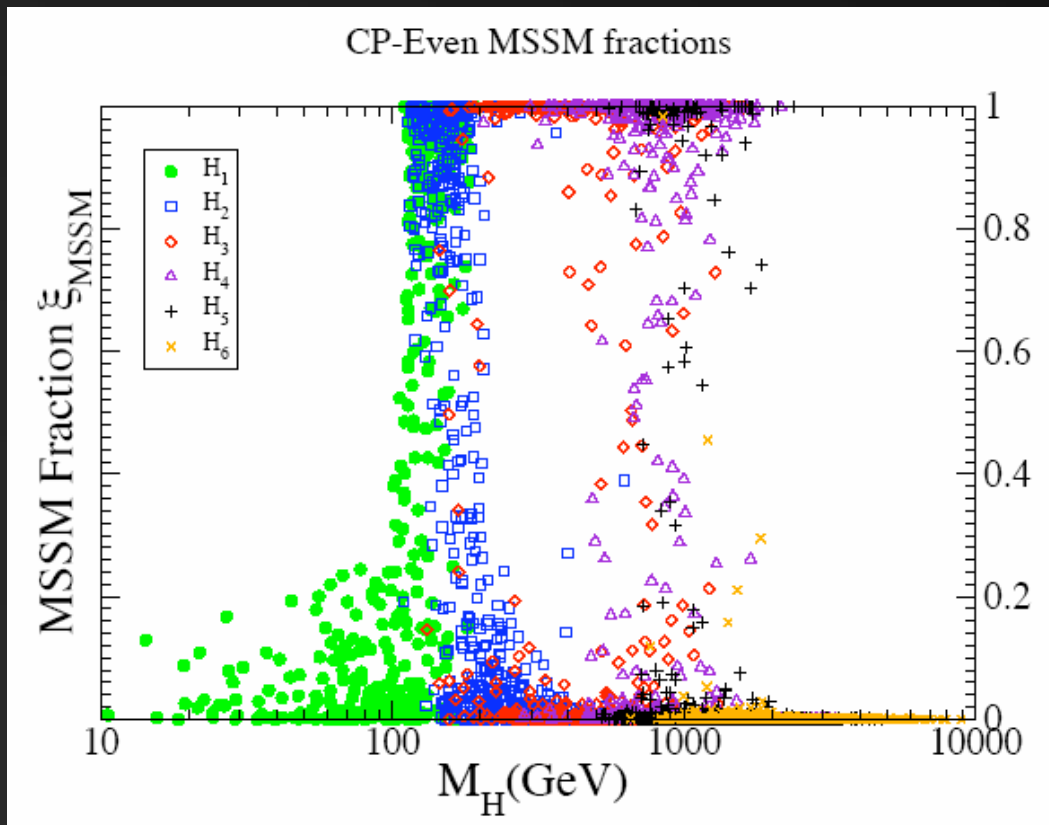


## (ex-i) Theoretical upper bound on the Higgs mass

- The upper bound on the lightest Higgs mass in Supersymmetric models is determined dominantly by the gauge couplings.
- With an additional gauge symmetry,  $U(1)'$ , the Higgs mass bound increases from that of the MSSM.
  - The lightest Higgs mass  $\lesssim 130$  GeV [MSSM]
  - The lightest Higgs mass  $\lesssim 170$  GeV [ $U(1)'$ -MSSM]

$$\begin{aligned} M_h^2 &\leq h^2 v^2 + (M_Z^2 - h^2 v^2) \cos^2 2\beta \\ &+ \frac{2g_{Z'}^2 v^2 (Q_{H_2} \cos^2 \beta + Q_{H_1} \sin^2 \beta)^2}{4v^2 \pi^2} \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}. \end{aligned}$$

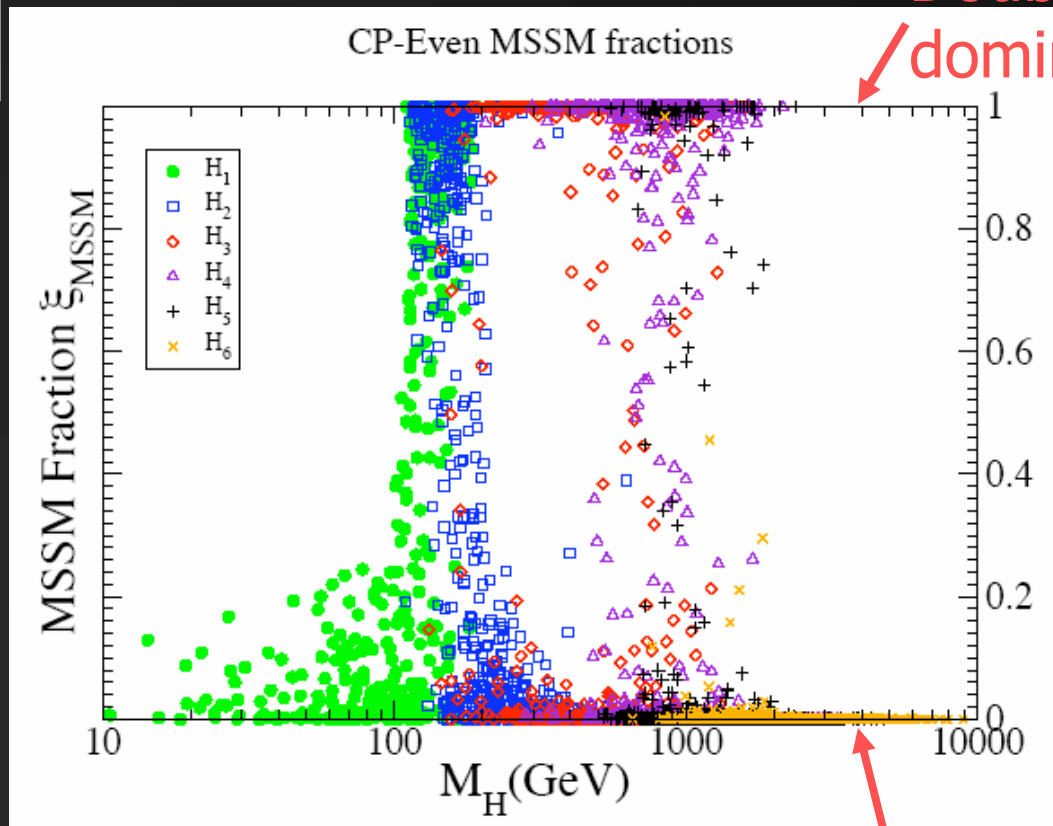
## (ex-ii) LEP2 lower bound on the Higgs mass



Han, Langacker, McElrath  
[PRD70 (2004) 115006]

- LEP2 constraint on the mass of the lightest Higgs (green dots) depends on the mixing status of the doublet and singlet (smaller ZZH for more singlet ratio).
- The SM-like lightest Higgs mass ( $m_h > 114$  GeV) does not apply.

## (ex-ii) LEP2 lower bound on the Higgs mass



Han, Langacker, McElrath  
[PRD70 (2004) 115006]

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Doublet-dominated

Singlet-dominated

Hye-Sung Lee

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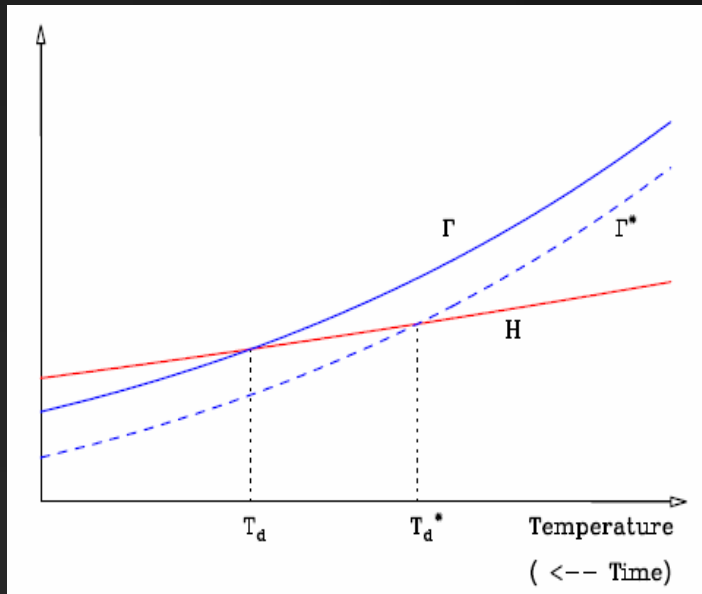
Higgs sector		
	MSSM	U(1)'-extended MSSM
Theoretical upper bound	$m_h \lesssim 130 \text{ GeV}$	$m_h \lesssim 170 \text{ GeV}$
LEP2 lower bound	$m_h > 114 \text{ GeV}$	$m_h \sim \mathcal{O}(10) \text{ GeV}$ is possible
Reason	$\text{SU}(2)_L$ doublet	Mixture of $\text{SU}(2)_L$ doublet and singlet under additional gauge



## (2) Neutrino sector

- If  $\nu_R$  carries a charge of the TeV-scale  $U(1)'$  symmetry,  
$$m_{\nu_R} \lesssim O(\text{TeV}).$$
- The Majorana mass of the  $\nu_R$  is not large enough for the ordinary seesaw mechanism.  
(Large mass is still possible if its charge is 0.)
- We assume **3 Dirac neutrinos with negligible masses**, not specifying a mechanism (e.g., extra dim) for light mass.
  - (ex-i) Big Bang Nucleosynthesis (BBN) constraint on  $Z'$
  - (ex-ii) Neutrinoless double beta decay ( $0\nu\beta\beta$ )

# (ex-i) Big Bang Nucleosynthesis (BBN) constraint on $Z'$

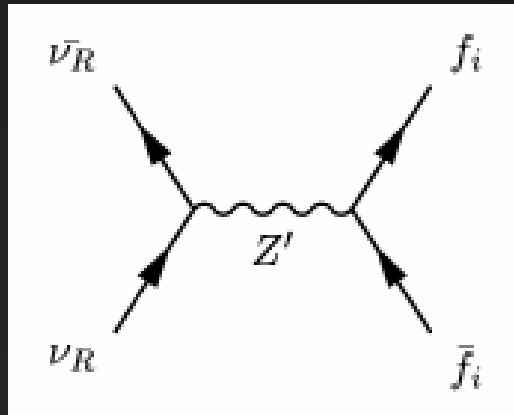


$\Gamma(T)$  : interaction rate of particle A

$H(T)$  : cosmological expansion rate

- For  $\Gamma > H$ , particle A is in equilibrium.  
For  $\Gamma < H$ , particle A is decoupled.
- Decoupling temperature ( $T_d$ ) of A, where  $\Gamma(T_d) = H(T_d)$ , carries information of interaction strength of A.






$$[G_{\text{SW}} \propto g_{Z'}^2/M_{Z'}^2] \ll [G_{\text{W}} \propto g_Z^2/M_Z^2]$$

for  $\nu_R$

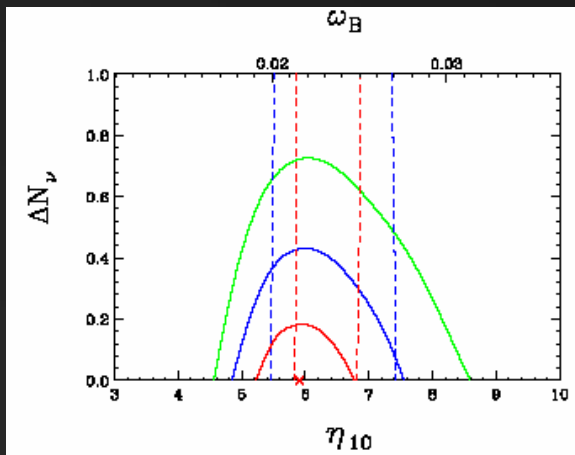
for  $\nu_L$

- $\nu_R$  is a particle with small interaction strength compared to that of  $\nu_L$  since it couples only to (very heavy)  $Z'$ .

- 
- Additional relativistic d.o.f. ( $\nu_R$ ) predicts larger primordial  $^4\text{He}$  abundance (by increasing expansion rate) from BBN.
  - Attribute this as the source of the uncertainty in the  $^4\text{He}$  abundance data ( $\Delta Y$ ) to constrain  $Z'$  property.
  - Larger mass of gauge boson (larger  $M_{Z'}$ )
    - smaller  $\Gamma$  of  $\nu_R$
    - earlier decoupling (from BBN era)
    - smaller  $\Delta Y$

Steigman, Olive, Schramm [PRL43 (1979) 239]

- A discrepancy in  $^4\text{He}$  abundance ( $Y$ ) data in terms of the effective L.H. neutrino number ( $N_\nu \propto Y$ ) :

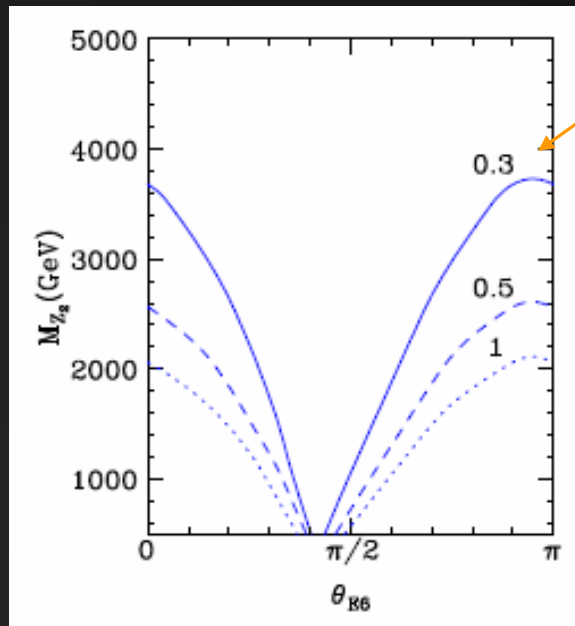


From BBN(+WMAP) data,  
 $\Delta N_\nu \leq 0.3$  at  $2\sigma$  level  
 (with  $N_\nu \geq 3$  condition).

Barger, Kneller, HL, Marfatia, Steigman  
 [PLB566 (2003) 8]

- $\Delta N_\nu$  value depends on the data and the analysis group but the typical range is  $\Delta N_\nu \leq (0.3 \sim 1)$ .

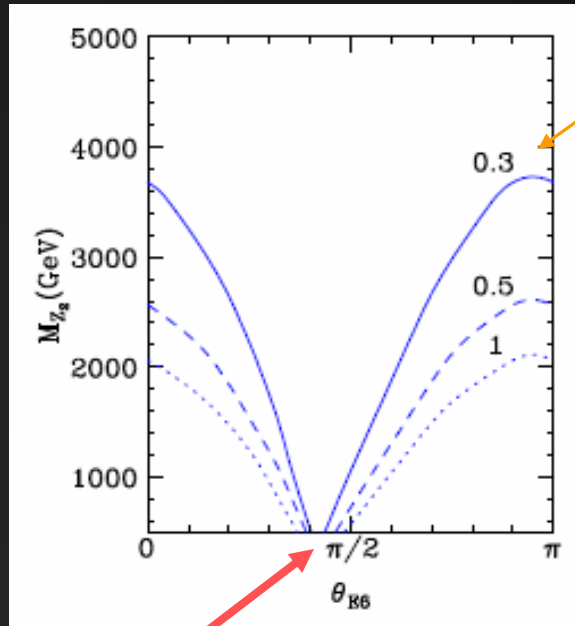
$M_{Z'}$   
lower  
bound



for a given  $\Delta N_\nu$   
(effective neutrino  
number)  $\propto \Delta Y$

Barger, Langacker, HL  
[PRD67 (2003) 075009]

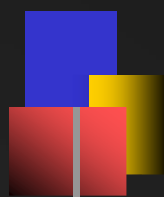
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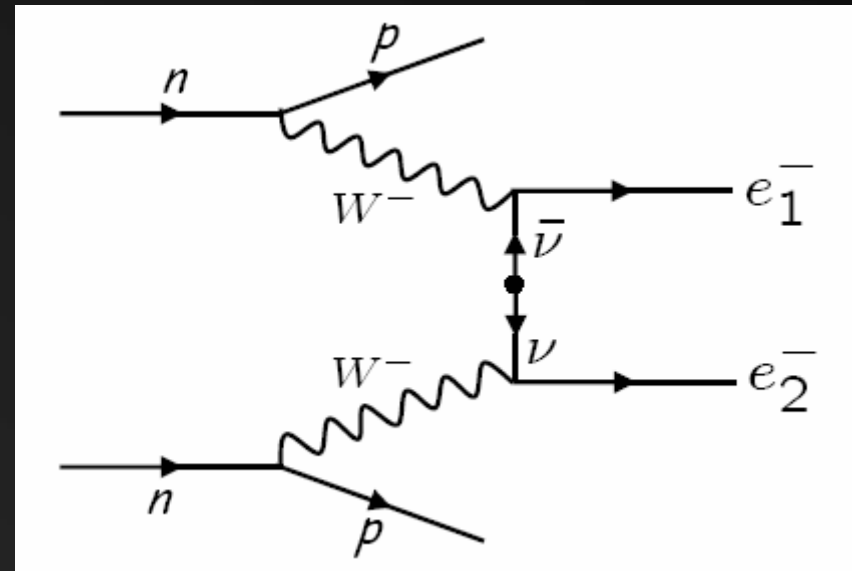
Barger, Langacker, HL  
[PRD67 (2003) 075009]

- At  $\theta_{E6}$  (mixing angle of 2 U(1)'s in  $E_6$  model) =  $0.42 \pi$ ,  $Q'(\nu_R) = 0$  ( $\nu_R$  does not couple to  $Z'$ ).
- BBN gives **the most stringent constraint** on  $Z'$  mass (mostly,  $M_{Z'} \sim$  multi-TeV).



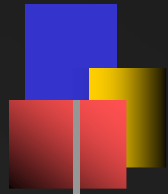
## (ex-ii) Neutrinoless double beta decay ( $0\nu\beta\beta$ )

- $0\nu\beta\beta$  is not generally expected to be observed ( $0\nu\beta\beta$  is possible for Majorana neutrinos).
- Still possible if  $Q'(\nu_R) = 0$ .





Neutrino sector		
	MSSM	U(1)'-extended MSSM
$\Delta N_\nu$ from BBN	No significant contribution to $N_\nu$ from superparticles	Discrepancy may be due to super-weakly interacting $\nu_R$
$0\nu\beta\beta$	(Usually) expected	Not expected [still possible]
Reason	Seesaw mechanism	U(1)' charged $\nu_R$ forms Dirac and couples to only (heavy) $Z'$



### (3) Neutralino sector

- Singlino and  $Z'$ -ino are added as the Supersymmetric partners of Higgs singlet and  $Z'$  boson.
- Neutralino sector is extended to 6-components [MSSM: 4, NMSSM: 5] with modified masses and couplings.



- Neutralino mass matrix in the basis of  $\chi^0 = \{\text{Bino}, \text{Wino}, \text{Higgsino}_1, \text{Higgsino}_2, \text{Singlino}, \text{Z'-ino}\}$ :

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\ 0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\ -g_1 v_1/2 & g_2 v_1/2 & 0 & -h_s s/\sqrt{2} & -h_s v_2/\sqrt{2} & g_{Z'} Q'(H_1^0) v_1 \\ g_1 v_2/2 & -g_2 v_2/2 & -h_s s/\sqrt{2} & 0 & -h_s v_1/\sqrt{2} & g_{Z'} Q'(H_2^0) v_2 \\ 0 & 0 & -h_s v_2/\sqrt{2} & -h_s v_1/\sqrt{2} & 0 & g_{Z'} Q'(S) s \\ 0 & 0 & g_{Z'} Q'(H_1^0) v_1 & g_{Z'} Q'(H_2^0) v_2 & g_{Z'} Q'(S) s & M_{1'} \end{pmatrix}$$


- Neutralino mass matrix in the basis of  $\chi^0 = \{\text{Bino}, \text{Wino}, \text{Higgsino}_1, \text{Higgsino}_2, \text{Singlino}, \text{Z'-ino}\}$ :

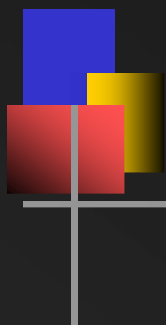
MSSM

NMSSM  
(with  $\kappa=0$ )

$U(1)'$

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\ 0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\ -g_1 v_1/2 & g_2 v_1/2 & 0 & -h_s s/\sqrt{2} & -h_s v_2/\sqrt{2} & g_{Z'} Q'(H_1^0) v_1 \\ g_1 v_2/2 & -g_2 v_2/2 & -h_s s/\sqrt{2} & 0 & -h_s v_1/\sqrt{2} & g_{Z'} Q'(H_2^0) v_2 \\ 0 & 0 & -h_s v_2/\sqrt{2} & -h_s v_1/\sqrt{2} & 0 & g_{Z'} Q'(S) s \\ 0 & 0 & g_{Z'} Q'(H_1^0) v_1 & g_{Z'} Q'(H_2^0) v_2 & g_{Z'} Q'(S) s & M_{1'} \end{pmatrix}$$

- 
- Neutralinos are important in many physics including
    - (ex-i) Cold dark matter (CDM) relic density
    - (ex-ii) Muon anomalous magnetic moment  $(g-2)_\mu$
  - MSSM can already reproduce acceptable CDM relic density and measured deviation of  $(g-2)_\mu$ .
  - $U(1)'$ -extended MSSM (with more parameters) can easily reproduce the similar results as the MSSM (without the  $\mu$ -problem).



- We consider a variant of  $U(1)'$ -extended MSSM [multiple singlets  $U(1)'$  model] which has more restrictions on parameter space and see if it still has solutions for these two experimental results.



## A Variant : Multiple singlets $U(1)'$ model

- 3 more Higgs singlets ( $S_1, S_2, S_3$ ) are added.
- Superpotential for the Higgs sector :

Erler, Langacker, Li [PRD66 (2002) 015002]


$$W_{S\text{-model}} = h_S S H_1 H_2 + \lambda_S S_1 S_2 S_3$$

- It can explain very heavy  $Z'$  (multi-TeV) easily while keeping  $\mu_{\text{eff}}$  at EW scale.

$$M_{Z'} = g_{Z'} [Q'(H_1)^2 v_1^2 + Q'(H_2)^2 v_2^2 + Q'(S)^2 s^2 + \sum_{i=1\sim 3} Q'(S_i)^2 s_i^2]^{1/2}$$

$$\mu_{\text{eff}} = h_S \langle S \rangle$$

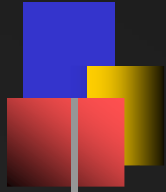
additional contributions  
from  $\langle S_{1,2,3} \rangle$

- 
- Interesting features of the multiple singlets model :
    - Small  $\tan\beta (= 1\sim 3)$  is required to be consistent with the EW symmetry breaking. ( $\rightarrow$  restricted parameter space)
    - Provides acceptable level of EWBG.  
*Kang, Langacker, Li, Liu [hep-ph/0402086]*
    - Typically, heavy masses for extra Singlino<sub>1,2,3</sub> limit works well to generate realistic values for Higgs doublets and singlet VEVs.  $\rightarrow$  We take this limit for calculation.



## (ex-i) Cold Dark Matter (CDM) relic density

- WMAP precise measurement of CDM relic density :  
 $0.09 < \Omega_{\text{CDM}} h^2 < 0.15$  ( $3\sigma$  allowed range)  
WMAP collaboration [APJ Sup148 (2003) 175]  
Barger, HL, Marfatia [PLB565 (2003) 33]
- The lightest neutralino ( $\chi^0_1$ ) is a strong candidate for the CDM, and it should reproduce the measured  $\Omega_{\text{CDM}} h^2$ .
- The lightest neutralino is often singlino-dominated and its mass bound is smaller than that of MSSM.  
(e.g., mass of  $\chi^0_1 < 100$  GeV for heavy  $Z'$ -ino)

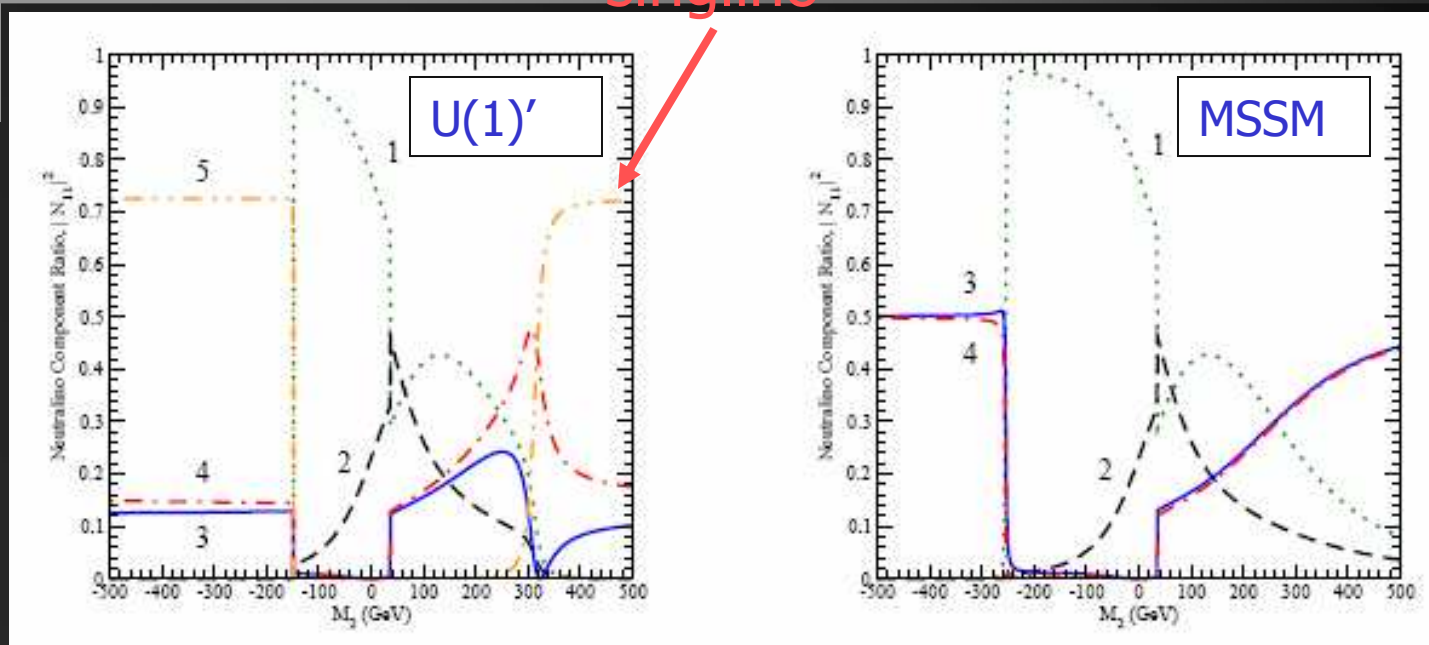


- $Z'$ -pole itself is too heavy to be a relevant annihilation channel.
- But, distinctive channels [from MSSM] can still arise because of the modified mass and coupling of the  $\chi^0_1$  : e.g., the  $Z$ - $\chi^0_1$ - $\chi^0_1$  coupling is enhanced even for small  $\tan\beta$ .





singlino

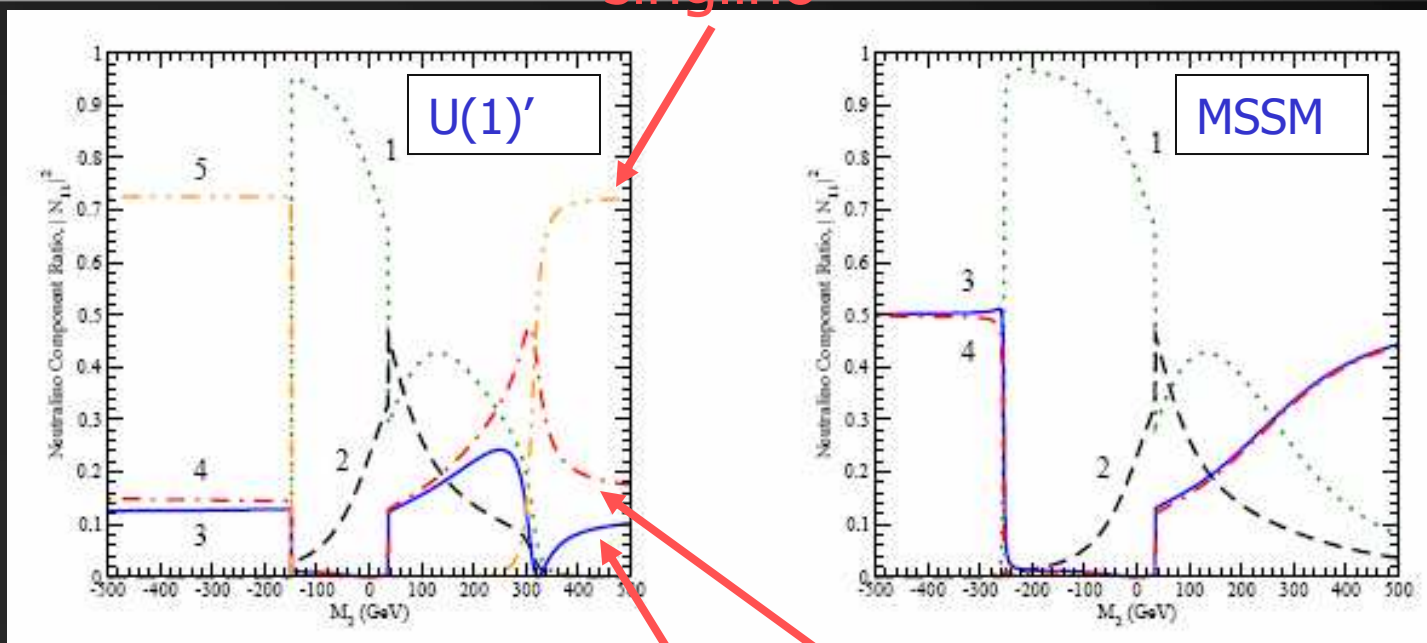


$\chi^0_1$  composition

- For  $\tan\beta \approx 1$ ,  
 $Z\text{-}\chi^0_1\text{-}\chi^0_1$  coupling  $\propto (|N_{13}|^2 - |N_{14}|^2)$   
 $\sim$  negligible [in MSSM]  
 $\sim$  sizable [in  $U(1)'$ -MSSM]

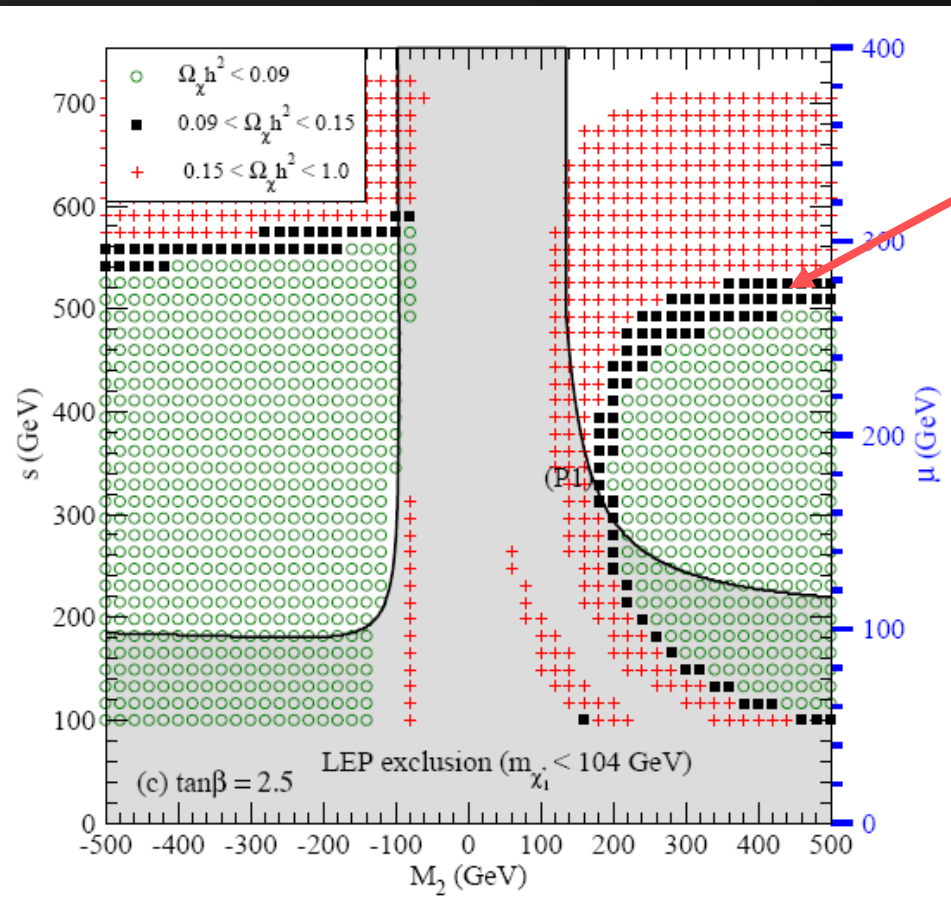


singlino



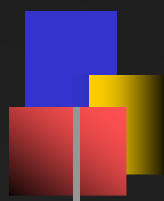
$\chi^0_1$  composition

- For  $\tan\beta \approx 1$ ,  
 $Z\text{-}\chi^0_1\text{-}\chi^0_1$  coupling  $\propto (|N_{13}|^2 - |N_{14}|^2)$   
 $\sim$  negligible [in MSSM]  
 $\sim$  sizable [in  $U(1)'\text{-MSSM}$ ]



- The acceptable CDM relic density ( $0.09 < \Omega_{\text{CDM}} h^2 < 0.15$ ) is reproduced even with only Z-pole channel [opening of a new channel].

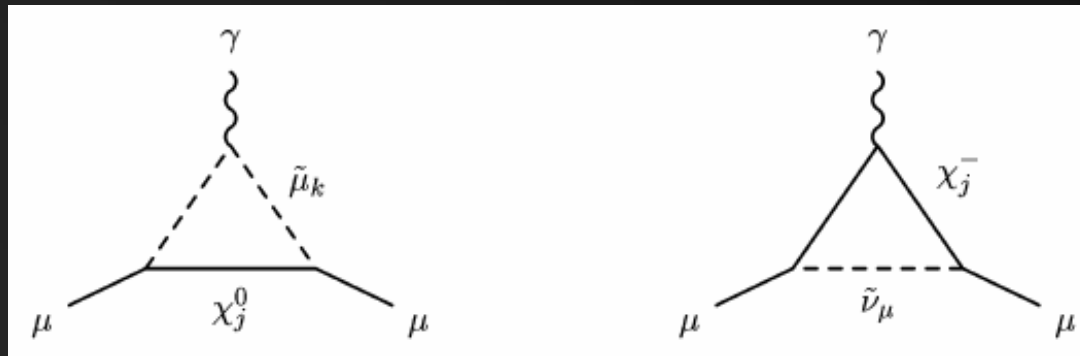
Barger, Kao, Langacker, HL PLB600 (2004) 104]



## (ex-ii) Muon anomalous magnetic moment $(g-2)_\mu$

- $(g-2)_\mu$  is one of the most precisely measured quantities.
- $2.4\sigma$  deviation from SM prediction ( $0.9\sigma$  if hadronic information is from indirect hadronic  $\tau$  decay) was found by BNL experiment (E821).
- New physics models are constrained by the deviation:
  - In MSSM,  $\text{sign}(\mu) > 0$ , upper limits on slepton masses
  - Compactification scale in an extra dimension
  - $Z'$  mass in  $U(1)'$  or GUT models (Collider limit of  $600 \sim 800$  GeV is too heavy to reproduce the deviation when only  $Z'$ -loop is considered)

- The same Supersymmetric contributions to  $(g-2)_\mu$  but with an extended neutralino sector exist.



- The  $\mu - \tilde{\mu}_k - \chi_j^0$  chiral couplings ( $j = 1 \sim 6$ ) :

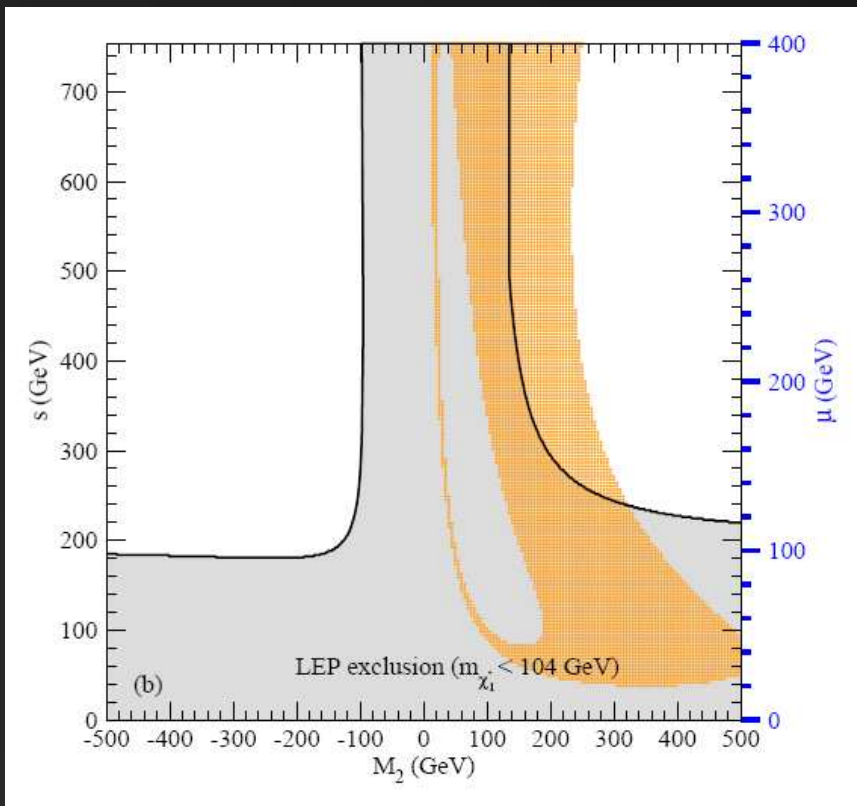
$$L_{jk} = \frac{1}{\sqrt{2}} \left( g_1 Y_{\mu_L} N_{1j}^* - g_2 N_{2j}^* + \underline{g_{Z'} Q'(\mu_L) N_{6j}^*} \right) D_{1k} + \frac{\sqrt{2} m_\mu}{v_1} N_{3j}^* D_{2k}$$

$$R_{jk} = \frac{1}{\sqrt{2}} \left( g_1 Y_{\mu_R} N_{1j} + \underline{g_{Z'} Q'(\mu_R) N_{6j}} \right) D_{2k} + \frac{\sqrt{2} m_\mu}{v_1} N_{3j} D_{1k}.$$

- 
- The Supersymmetric contribution to  $(g-2)_\mu$  in the limit of degenerate Supersymmetric masses :

$$\Delta a_\mu(\text{SUSY}) \sim 13 \times 10^{-10} \frac{\tan \beta \operatorname{sign}(\mu)}{(M_{\text{SUSY}}/100 \text{ GeV})^2}$$

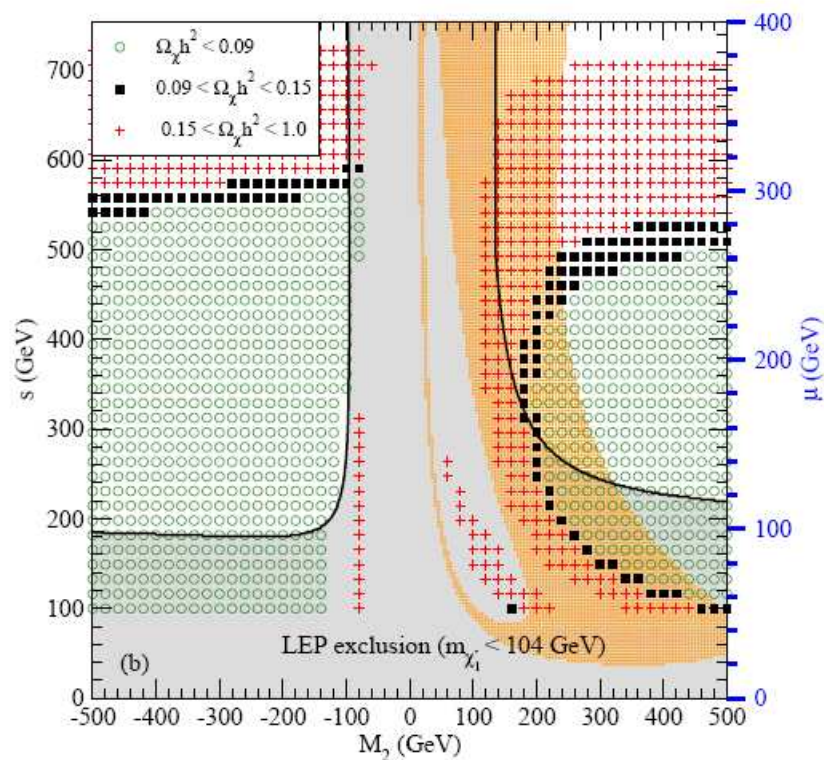
- The chargino and neutralino loop contributions are proportional to  $\tan\beta$ .
- Since  $\tan\beta$  is small ( $= 1\sim 3$ ) in the multiple singlets  $U(1)'$  model, it is not clear if it can explain the  $(g-2)_\mu$  deviation.



- The solutions exist that explain  $(g-2)_\mu$  even with a small  $\tan\beta$  (if mass of  $\text{smuon} < 180$  GeV).
- The solution space is larger than MSSM.

Barger, Kao, Langacker, HL  
[hep-ph/0412136]

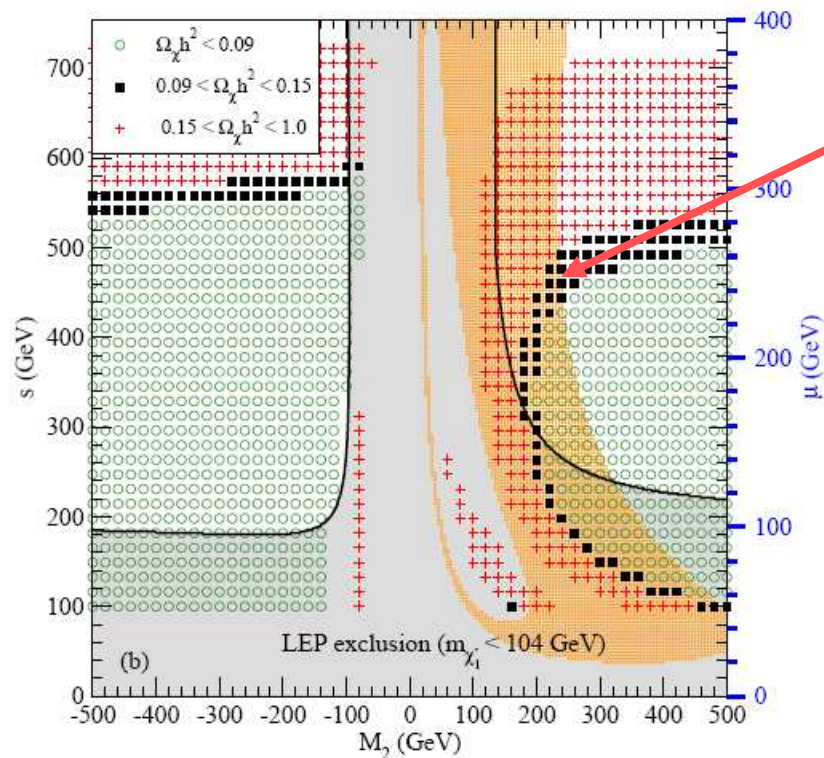




- **Common solutions** exist that explain  $(g-2)_\mu$  and WMAP CDM relic density simultaneously.

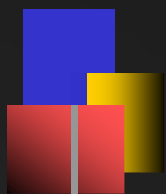
Barger, Kao, Langacker, HL  
[hep-ph/0412136]





- **Common solutions** exist that explain  $(g-2)_{\mu}$  and WMAP CDM relic density simultaneously.

Barger, Kao, Langacker, HL  
[hep-ph/0412136]



Neutralino sector		
	MSSM	multiple singlets $U(1)'$
LSP	typically Bino-dominated	typically Singlino-dominated
CDM relic density	For $\tan\beta \approx 1$ , Z-pole is irrelevant.	For $\tan\beta \approx 1$ , even Z-pole alone can reproduce.
$2.4\sigma$ of $(g-2)_\mu$	Can explain	Can explain even with small $\tan\beta$ and constrains smuon mass $< 180$ GeV.
Reason	4 component neutralino	6 component (singlino and $Z'$ -ino) neutralino



## (4) Gauge boson sector [with CP & FCNC]

- In  $U(1)'$ -extended models, extra sources of the CP phase exist due to the Higgs singlet in superpotential and soft term.

Demir, Everett [PRD69 (2004) 15008]

- Additional CP phase and Flavor Changing Neutral Current (FCNC) are possible if  $Z'$  has a family non-universal coupling (allowed in certain types of the String-motivated models).

Langacker, Plumacher [PRD62 (2000) 13006]

(Ex) Left-handed  $d$ -type quark  $U(1)'$  coupling matrix

$$\begin{aligned}\mathcal{L} &= -g_{Z'} Z'_\mu (\bar{d}_L^{\text{int}} \gamma_\mu \epsilon_{d_L} d_L^{\text{int}}) \\ &= -g_{Z'} Z'_\mu (\bar{d}_L \gamma_\mu B^L d_L)\end{aligned}$$

- $U(1)'$  coupling matrix in interaction eigenstate ( $d_L^{\text{int}}$ ):

$$\epsilon_{d_L} = Q_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \delta \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- $U(1)'$  coupling matrix in mass eigenstate ( $d_L = V_{d_L} d_L^{\text{int}}$ ):

$$\begin{aligned}B^L &\equiv V_{d_L} \epsilon_{d_L} V_{d_L}^\dagger = Q_{d_L} V_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \delta \end{pmatrix} V_{d_L}^\dagger \\ &= \begin{cases} Q_{d_L} \mathbf{1}_{3 \times 3} & (\text{if } \delta = 0) \\ \text{general } 3 \times 3 \text{ matrix} & (\text{if } \delta \neq 0) \end{cases}\end{aligned}$$

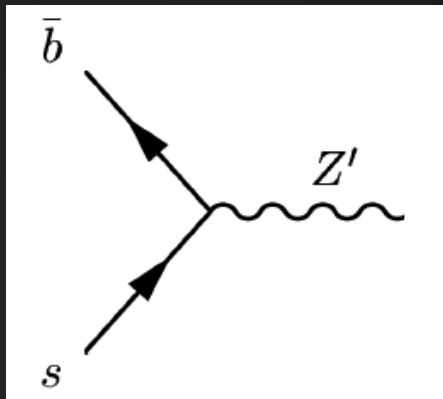
$B^L$  has off-diagonal terms with phases originated from  $V_{d_L}$ . (And similarly for  $u$ -type quark and/or Right-handed coupling.)

The usual CKM matrix is given by  $V_{CKM} = V_{u_L} V_{d_L}^\dagger$ .

non-universal but still  
no FCNC in interaction  
eigenstate

induced FCNC and  
phases in mass  
eigenstate

- FCNC by  $Z'$  is suppressed by its large mass, but it is tree-level while SM FCNC are all loop-suppressed.
  - (ex-i) Rare B-decays ( $B_d \rightarrow \pi K$ ,  $B_d \rightarrow \phi K_S$ )
  - (ex-ii) EW Precision Test ( $A_{\text{FB}}^{0,b}$ )





## (ex-i) Rare B-decays ( $B_d \rightarrow \pi K$ , $B_d \rightarrow \phi K_S$ )

- [B  $\rightarrow \pi K$  puzzle]

B  $\rightarrow \pi K$  branching ratios showed  $2.4\sigma$  [early 2004] deviation from the SM (by separate BaBar, Belle, CLEO data). Data suggests NP effect in EW Penguin sector.

- [B  $\rightarrow \phi K_S$  CP anomaly]

B  $\rightarrow \phi K_S$  is NP-sensitive since SM contribution is only loop-order. Belle data showed its CP asymmetry ( $S_{\phi K}$ ) deviated by  $3.5\sigma$  [early 2004] from the SM.

- *The deviations are reduced in the recent data, but still show the discrepancies ( $\sim 2\sigma$  levels).*

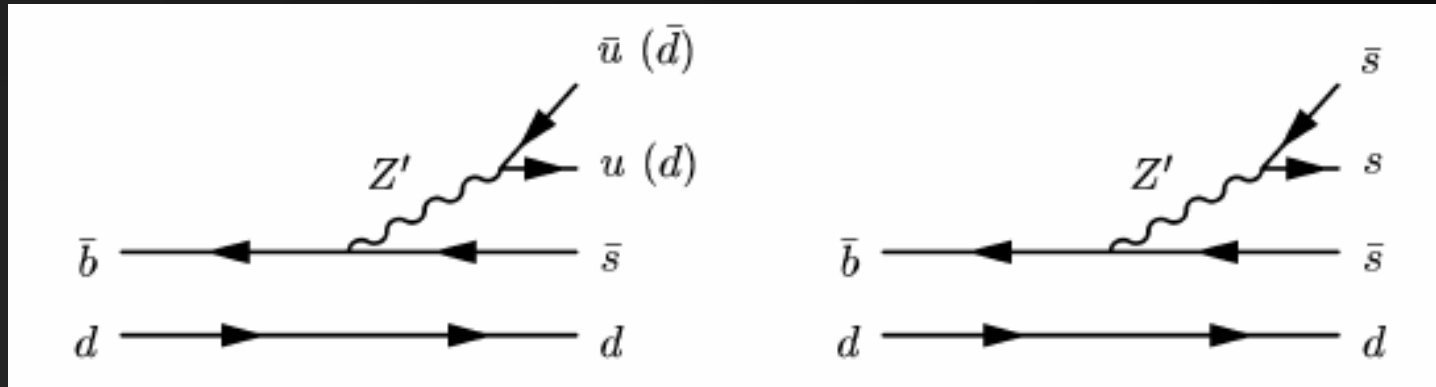
- $Z'$  contribution simplified (to reduce parameters) :  
 (1) only to EW Penguin sector (suggested by  $B \rightarrow \pi K$ )  
 (2) flavor-changing only for left-handed coupling

- Effective Hamiltonian for  $b \rightarrow s$  flavor-changing  $Z'$  is

$$\Delta \mathcal{H} = \sqrt{2} G_F \left( \frac{g_{Z'} M_Z}{g_Z M_{Z'}} \right)^2 B_{sb}^{L*} (\bar{b}s)_{V-A} \sum_q \left( B_{qq}^L (\bar{q}q)_{V-A} + B_{qq}^R (\bar{q}q)_{V+A} \right) + \text{h.c.}$$

- Contributions to the EW Penguin coefficients ( $c_9, c_7$ ) are

$$\Delta c_{9(7)} = \frac{4}{V_{tb}^* V_{ts}} \left( \frac{g_{Z'} M_Z}{g_Z M_{Z'}} \right)^2 B_{sb}^{L*} B_{dd}^{L(R)}$$

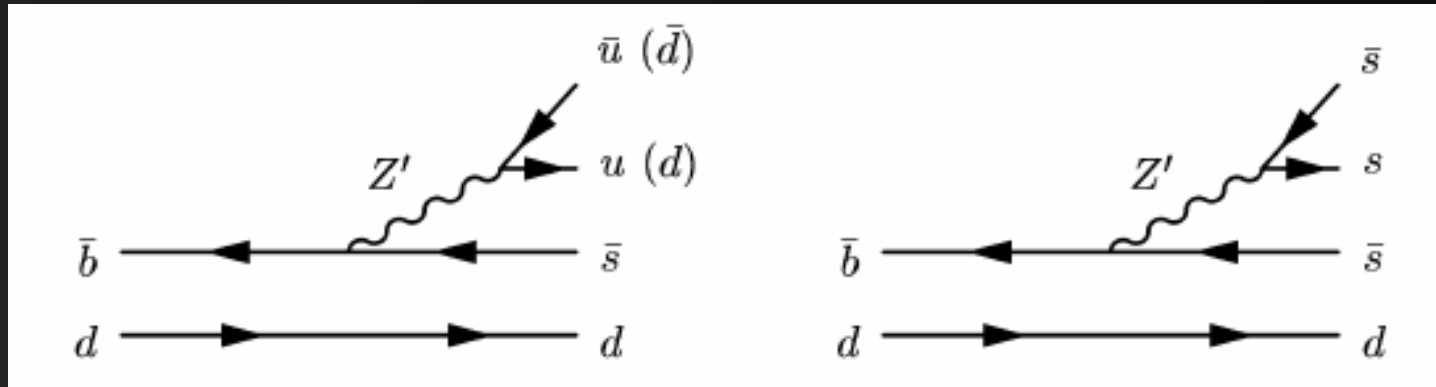


Barger,Chiang,Langacker,HL  
[PLB598 (2004) 218]

Barger,Chiang,Langacker,HL  
[PLB580 (2004) 186]

- Both  $B \rightarrow \pi K$  and  $B \rightarrow \phi K_S$  anomalies can be successfully explained with a TeV-scale flavor-changing  $Z'$  with **common parameter values** without conflicts with related experiments such as  $B \rightarrow \eta' K_S$  and Mercury EDM (Electric Dipole Moment).





Barger,Chiang,Langacker,HL  
[PLB598 (2004) 218]

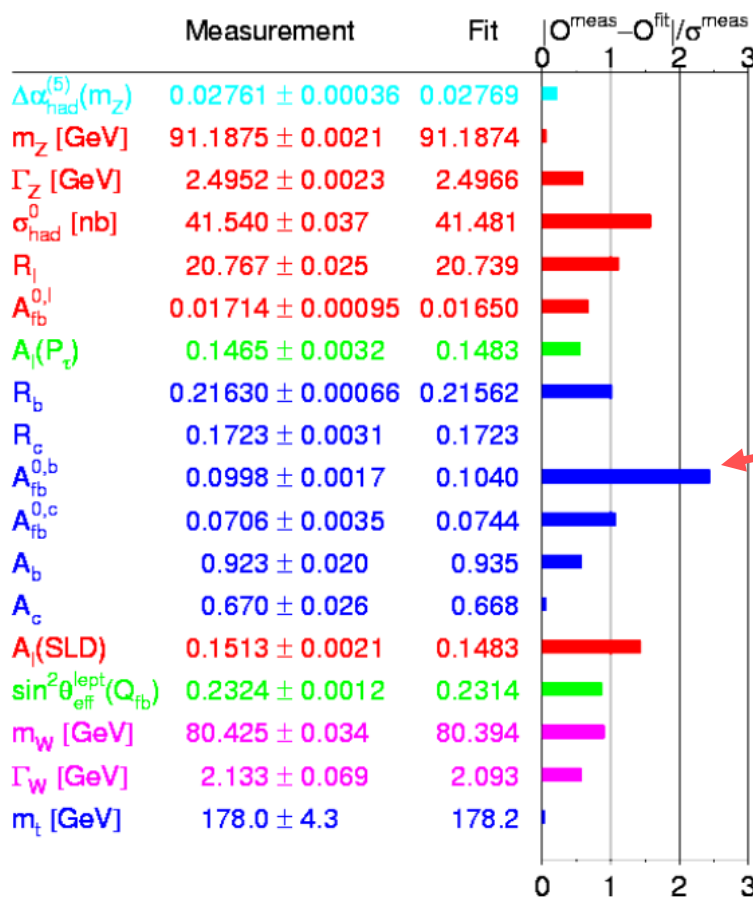
Barger,Chiang,Langacker,HL  
[PLB580 (2004) 186]

- Both  $B \rightarrow \pi K$  and  $B \rightarrow \phi K_s$  anomalies can be successfully explained with a TeV-scale flavor-changing  $Z'$  with **common parameter values** without conflicts with related experiments such as  $B \rightarrow \eta' K_s$  and Mercury EDM (Electric Dipole Moment).

# (ex-ii) EW Precision Test


EWWG

Summer 2004



- EW precision data agree well with SM.
- The largest discrepancy is the  $2.5\sigma$  of  $A_{FB}^{0,b}$ .

Riemann [Northwestern Workshop on Z's (Nov '04)]

- 
- The  $2.5\sigma$  discrepancy of  $A_{\text{FB}}^{0,b}$  may be due to the NP affecting preferentially the 3rd generation with sizable effect.
  - The tree-level FCNC by  $Z'$  may be the source of the  $A_{\text{FB}}^{0,b}$  discrepancy.
  - The TeV-scale  $Z'$  with different 3<sup>rd</sup> family coupling can provide a better fit for the EW precision data.

Erler, Langacker [PRL84 (2000) 212]



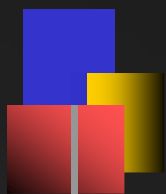
## Gauge Boson sector [with CP & FCNC]

	MSSM	$U(1)'$ -extended MSSM
Rare B decays	Some Supersymmetric solutions exist.	Supersymmetric solutions + additional flavor-changing $Z'$ solutions exist.
EWPT		$A_{FB}^{0,b}$ may be due to flavor-changing $Z'$ .
Reason	FCNC by loops of superparticles	$Z'$ -mediated FCNC can be sizable at tree-level.

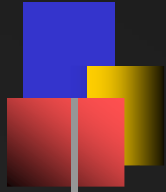


## 5. Summary

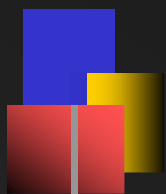
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- SM was extended to the Supersymmetric model to resolve the fine-tuning problem (gauge hierarchy problem), but its minimal model (MSSM) has its own fine-tuning problem ( $\mu$ -problem) related to Higgs mixing parameter.
- $U(1)'$ -extended MSSM may be a natural extension of the MSSM : It solves the  $\mu$ -problem and is rationalized by many new physics models that predict additional  $U(1)$  symmetries. [GUT, Extra dim, String, Strong dynamics, Little Higgs]



- Solution of  $\mu$ -problem implies EW/TeV-scale for the  $U(1)'$  gauge boson  $Z'$ . (LHC can search up to 5 TeV.)
- Particle spectrums are extended in the  $U(1)'$ -extended MSSM [Gauge boson, Higgs, Neutralino, Neutrino] and properties of “important” particles [light Higgs, lightest neutralino (LSP)] may change.



- The extended/modified particle spectrum serve as rich source of phenomenology :
  - High-E collider [ $Z'$ , Higgs]
  - Non-collider [ $0\nu\beta\beta$ ,  $(g-2)_\mu$ ]
  - Astro/Cosmology [BBN, CDM relic density]
  - Rare decays [ $B_d \rightarrow \pi K$ ,  $B_d \rightarrow \phi K_S$ ]
  - EWPT [ $A_{FB}^{0,b}$ ]
- A crucial check of the model is to observe a TeV-scale resonance and to identify it using collider and the other data.





## For more about $U(1)'$ -extended MSSM

- For more details and references for the  $U(1)'$ -MSSM or  $Z'$ , please visit my website :

### The $Z'$ Hunter's Guide

<http://pheno.physics.wisc.edu/~comety/hunter/>

(Try The  $Z'$  Hunter's Guide at )

[maintained to be up-to-date]